

# Changes in the riparian zone of the lower Eygues River, France, since 1830

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**Abstract** The riparian forests along braided rivers are dynamic, frequently rejuvenated by floods and channel changes, and thus dominated by pioneer to middle stages of succession; they are sites of high biodiversity in some regions. The Lower Eygues River (drainage area 1150 km<sup>2</sup> in southeastern France) is such a braided river system with large alluvial forests dominated by *Salix alba*, *Populus alba*, and *P. nigra*. It was identified as a site of ecological interest by the EU under the *Natura 2000* program. Such forests elsewhere in Europe have been identified as reference ecosystems. We documented the historical evolution of this alluvial forest from detailed (1:2500 scale)

early 19th C parcel maps, early 20th C topographic maps, aerial photography from 1947 to 1996, and field surveys of topography and riparian vegetation in 1997–1998. Our results show that in 1830, the channel was wide, aggraded, and agricultural pressure extended literally to the channel edge. With decline in the rural population and reduced agricultural and grazing pressure in the catchment, erosion rates declined. Reduced sediment supply led to channel narrowing and incision. This channel narrowing, coupled with reduced agricultural pressure along the banks, has allowed riparian forest to colonize former active channel areas, especially within late 19th-century 20th century flood dykes. In recent decades, aggregate mining, and clearing for recreation and agriculture have fragmented the forest. Thus, the alluvial forest of the Lower Eygues is largely an artifact of changing human land-use over the past century, a context that should frame efforts for preservation and restoration.

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conservation · riparian vegetation

## Introduction

Riparian corridors are increasingly recognized as important elements of river systems, occupying the transition between terrestrial and aquatic

ecosystems, and constituting habitats with an often disproportionately large ecological importance (Naiman et al. 1993; Malanson 1993; NRC 2002; Hughes 2003). Riparian corridors are characterized by high diversity of species and plant communities, are important sources of food, energy, and nutrients to aquatic environments, act as buffers protecting water quality from agricultural runoff, and provide aquatic habitat by shading the channel, introducing large woody debris to the channel, and creating shelters by roots in the bank (Schiemer and Zalewski 1992; Tabacchi and Planty-Tabacchi 1996; Piégay et al. 2003).

Most research has focused on the riparian forests of temperate-climate, meandering rivers, with their potential to develop mature, equilibrium vegetation (Marston et al. 1995; Greco and Plant 2003). Along braided rivers, riparian forests can be important, although with different characteristics. Riparian vegetation is dominated by pioneer to middle stages of succession (Amoros and Petts 1993), the forests are dynamic, and often rejuvenated by floods and channel changes. Braided floodplains can constitute sites of high biodiversity in some areas (Burgherr et al. 2002; Tockner and Stanford 2002). The Lower Eygues River (i.e., the reach downstream from Nyons) is such a braided system with large alluvial forests comparable to those observed along the neighboring Roubion and Drôme Rivers (Fig. 1) (Piégay and Landon 1997) or along the Tagliamento River in northern Italy (Ward et al. 1999).

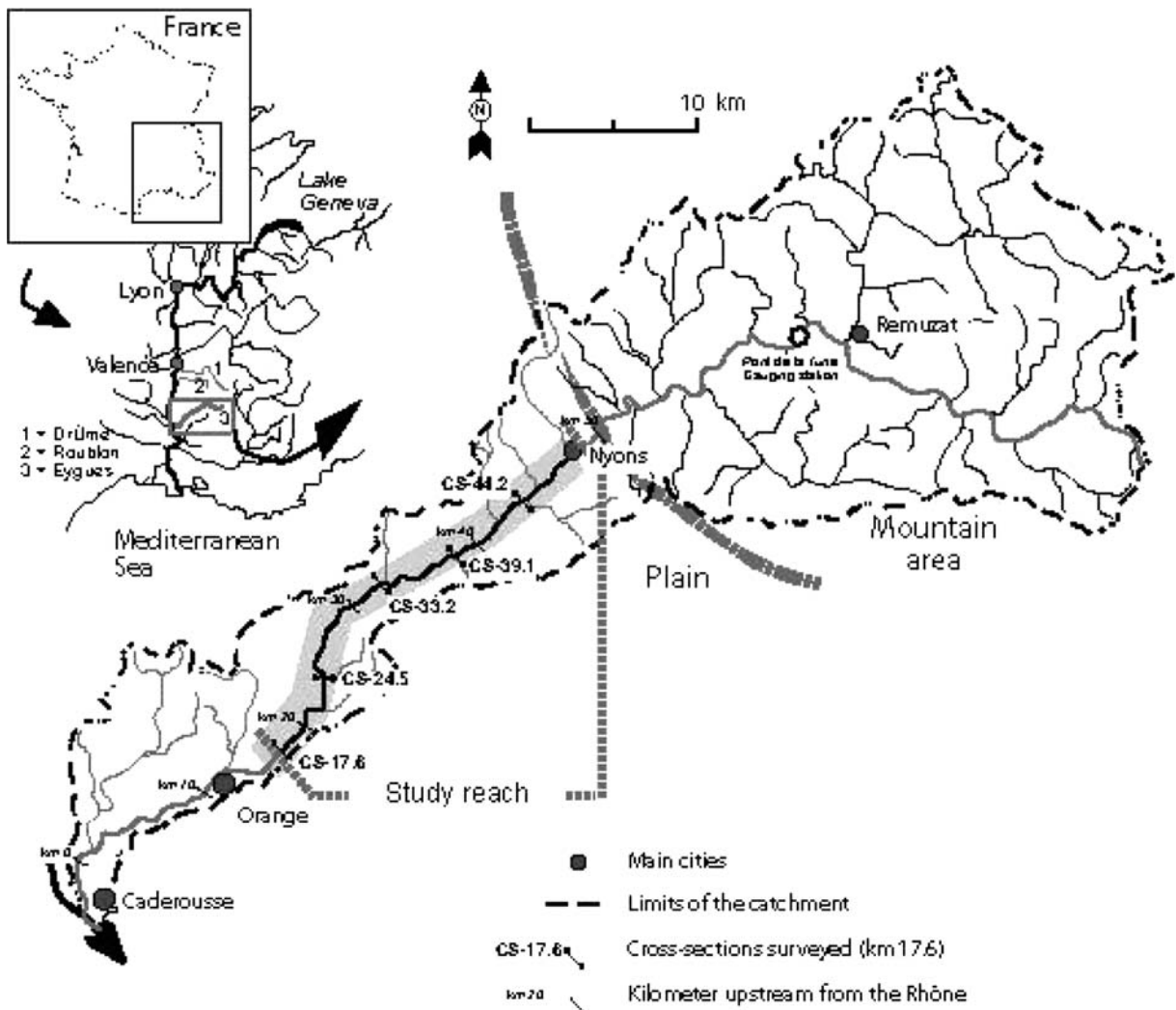
The riparian forest of the Eygues was identified as a key ecosystem by the European Community under the *Natura 2000* program (<http://www.natura2000.environment.gouv.fr/sites/FR8201689.html>) in recognition of its forest corridor of *Salix alba*, *Populus alba*, and *P. nigra*, species that are well-adapted to withstand floods and recolonize fresh sediment deposits (Karrenberg et al. 2002). Such braided rivers with well-developed riparian forests take on increased importance as alluvial forests disappear elsewhere, especially in the developed countries of Europe. Moreover, such channels have been identified as natural “reference states” for alluvial forest restoration (Tockner et al. 2003). However, in this paper we show that the alluvial forest ecosystem of the Eygues is largely a legacy of past and current

human land use and geomorphic adjustment. In a landscape shaped by long-term human land use, the concept of ecosystem services may be more appropriate basis for setting restoration goals than a reference state.

## Study Area

The Eygues River (also written as Aigues or Aygues, a corruption of the latin *aqua*) drains 1150 km<sup>2</sup> in the Baronnies Mountains, in the southern PreAlps of France, debouching into the Rhône Valley at Nyons, and flowing 48 km through an alluvial plain to its confluence with the Rhône River at Orange (1100 km<sup>2</sup>)(Fig. 1). The Eygues has a mean annual flow of 6.22 m<sup>3</sup> s<sup>-1</sup> and a 10-year flood of 270 m<sup>3</sup>-s<sup>-1</sup> at Pont-de-la-Tune (drainage area 473 km<sup>2</sup>) based on gauging records from 1906–2003. Active channel width from Orange to Nyons averages 140 m, with slope decreasing from 0.007 near Nyons to 0.004 near Orange, and to less than 0.002 further downstream. The median grain size ranges from 25 to 35 mm. The Eygues River catchment ranges in elevation from 67 m at the Rhône River confluence to 1757 m at the divide. The catchment is underlain primarily by limestones and marls of Cretaceous and Jurassic age. The climate is Mediterranean, with cool, wet winters and warm, dry summers. September through November receive 35% of annual precipitation, some as infrequent, intense, localized thunderstorms, which produce the largest floods. In September 1992 117.5 mm of rain fell in 2.5 h at Nyons (Blanchet and Deblaere 1993), producing a record peak discharge of 830 m<sup>3</sup> s<sup>-1</sup> at Nyons and 850 m<sup>3</sup> s<sup>-1</sup> at Orange.

The valley of the Eygues downstream of Nyons is heavily developed for agriculture, principally vineyards and orchards. Since the 18th and 19th centuries, water has been diverted from the Eygues at many sites to run mills or for irrigation. Dykes have been constructed along the river banks in some reaches to train the channel or prevent flooding, many first built in the 19th century, and at least one (protecting the city of Nyons along the right bank) dating back to the 18th century. Gravel has been extracted from the active channel bed



**Fig. 1** Location map, showing Eygues River basin and study reach downstream of Nyons, and neighboring rivers

and from pits on the adjacent floodplain at several sites through the 20th century, up until 1992, when most commercial mining was outlawed (Landon and Piégay 1999).

## Methods

We undertook a reach-level characterization of changes in the riparian corridor by recording land uses in parcels adjacent to the river, channel widths, and incision as indicated from long profiles, using evidence from 1830 cadastral maps and land ownership records, from aerial photographs

(for 1947 to present), and long profiles (for 1931 to present). To create a common framework within which to record and analyze diverse data sources, we first measured distance upstream from the Rhône River confluence on the IGN 1:25 000 topographic maps, and thereafter designated locations along the channel by their distance in km upstream of the Rhône, e.g., “km 10” (Fig. 1).

## Historical planform evolution

We were fortunate to have access to the Napoleonean cadastral maps, a remarkable set of detailed (1:2 500 scale) parcel maps, dating from

the early 19th century which show individual numbered parcels, with land use indicated on an accompanying table. The dates of these cadastral maps varied among communes from 1824 to 1830. To simplify data presentation we use the date of 1830 when referring to the cadastral surveys in general, but we use the actual date when referring to a specific cadastral map. We examined the cadastral maps at the Archives Départementales de la Drôme in Valence, the Service des Impôts du Vaucluse (tax assessor) in Orange, and the Commune of Nyons. We also examined departmental records pertaining to bridges and dykes, which included maps showing existing channel conditions and proposed dykes back to the early 19th century. We examined 20th century topographic maps and aerial photographs to measure channel widths, document riparian land use, and map the occurrence of stands of riparian vegetation large enough to map. We analyzed aerial photographs dated 1947–1948, 1972, and 1996. The 1947 flight covered the river downstream of Nyons, the 1948 flight upstream; henceforth we refer to the date of these photos simply as 1947. Many of the forest units present today were bare channel or sparse scrub on the 1947 aerial photographs, allowing us to establish maximum ages for those units.

The riparian forest is best developed from km 14 to 48, so we focused our study there. For each 500-m section of the study reach (km 0–0.5, km 0.5–1.0, etc.), we drew a transect line across the riparian corridor at the midpoint of the section. To document existing conditions in the riparian forests along the Eygues, we examined 1996 color aerial photography (scale 1:25 000) covering the 48-km reach from Nyons downstream to the Rhône River confluence, and mapped the extent of the riparian forest and its major units, identifying polygons of vegetation by their distinctive height and texture on aerial photographs, calibrated by direct field observations in 1998. We used the field-calibrated data from 1996 air photos to map vegetation units on the 1947 air photos, and we used map notations for the units on the 1830 cadastral map. We measured the width of active channel, stands of riparian vegetation, etc., thereby generating a set of 67 data points with which to quantify changes in width of the fluvial

corridor occupied by riparian vegetation, unvegetated channel, and other land cover types.

### Cross Section and Long Profile Surveys

From field reconnaissance and examination of the vegetation patterns on recent aerial photographs, we identified five sites characterized by a relatively natural channel and a well-developed forest that included different ages of vegetation representative of the forest units along this reach. At each of these sites, we established cross sections perpendicular to the channel through the vegetation units. At each of these five sites (at km 17.6, 24.5, 33.2, 39.1, and 44.2), we surveyed a cross section (designated as CS 17.6, CS 24.5, etc) across the floodplain and channel, encompassing the entire riparian forest. We surveyed topography, identified dominant tree species present on different surfaces along a belt transect 2 m wide, and determined the depth of overbank sediments with a soil auger, making two to five observations per sediment unit. We used results of this field work (conducted in 1998) to calibrate our interpretations of the riparian vegetation stands visible on the 1996 aerial photographs. No large floods occurred on the Eygues between the date of the air photos and our field work, so conditions shown on the air photos corresponded closely to those we observed in the field. By comparing field observations with current and historical maps and air photos, we identified surfaces dating from the early 19th century to present.

We analyzed longitudinal profiles of the river surveyed in 1931 by *Service des Grandes Forces Hydrauliques* (a state service charged with locating sites suitable for hydro-electricity production), in 1985 by SOGREAH (a consulting firm based in Grenoble), both continuous from Nyons downstream to the Rhône. We surveyed a new long profile survey in 1997 for the same river length at low flow and measured changes in bed elevation over time. Using historical evidence for plan-form and vertical elevation changes, and the field relations we documented in our cross sections, we reconstructed the evolution in channel form.

## Results

### Current state of the riparian forest

The riparian forest in 1996 was not continuous, but flanked well over half the banks, and would be more extensive but for areas cleared for agricultural, industrial, and urban uses (Fig. 2). The vegetation surveys along the cross sections (Fig. 3), supported by analysis of the aerial photographs, show that the riparian corridor is characterized by two principal vegetation associations: a poplar (*Populus nigra* and *P. alba*)-dominated unit, and an alder (*Alnus glutinosa*)-dominated unit. The poplar unit colonizes gravel bars, which characterize most of the surface abandoned by the formerly active channels. Its early successional stands consist of poplars mixed with shrubby willows (*Salix alba*) mainly. In later successional stands, an understory of ash (*Fraxinus angustifolia*), elm (*Ulmus minor*), and young oaks (*Quercus pubescens* and *Quercus ilex*) occurs. Robinia, or black locust (*Robinia pseudoacacia*), an invasive species occurs in some recently-harvested units. By the time the poplar units are 20 years old, they present an extremely dense understory, which may include dogwood (*Cornus sanguinea*), hazel (*Corylus avellana*), and hawthorn (*Crataegus monogyna*).

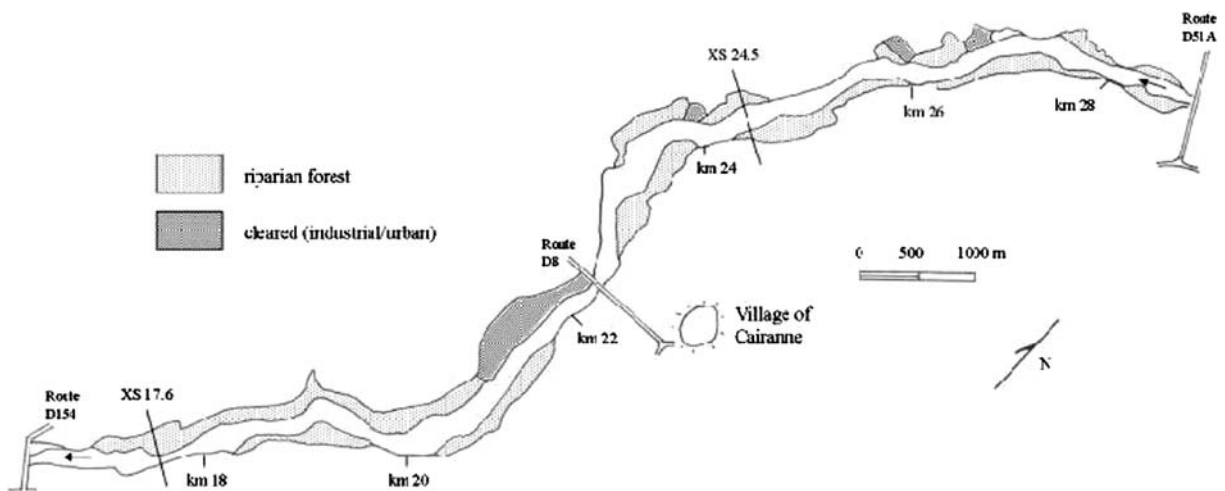
The alder-dominated association tends to occur near the margins of the corridor, at the foot of terraces, environments with more fine

sediment, and which also tend to be more humid thanks to groundwater seeping from the terraces. In some cases, this groundwater seepage is probably supported in part by irrigation of agricultural lands on the terraces. The alder unit occurs in monospecific stands, mixed with poplars (especially along channel margins), and in some cases (such as the right bank of CS 44.2) associated with white willow.

On levees and areas devegetated for human use, oaks occur. Where the terraces have been cleared of vegetation for human use and then abandoned, the cleared surfaces are not colonized by poplars or other pioneer species, as these cannot establish on these now-xeric surfaces above the incised channel. Rather, they tend to be vegetated by an assemblage of plants that is more open, and which contains more xerophytic and thermophylic plants. Holm oak (*Quercus ilex*), broom (*Ginesta spp.*), and argousier (*Hypophae ramnoïdes*) occur with mature individuals of the understory species such as hedge (*Ligustrum vulgare*), and dogwood, as illustrated on the right bank of CS 24.5 (Fig. 3).

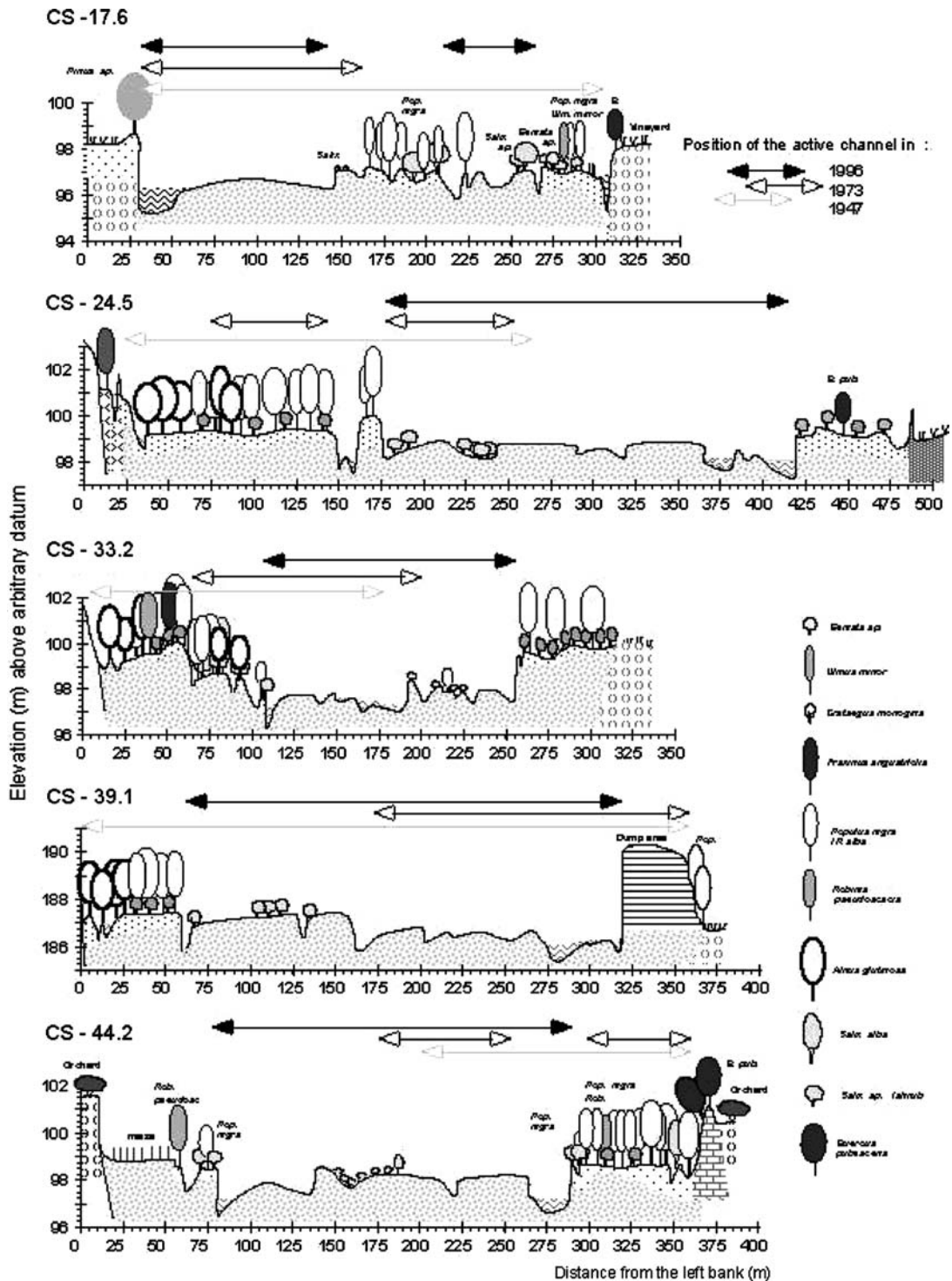
### Changes in riparian zone since the 19th century

The banks of the early 19th-century channel were intensely managed by humans, with many small



**Fig. 2** Map of riparian forest along the Lower Eygues River from km 16.4 to 28.8, drawn from 1996 aerial photographs at 1:25 000 scale (source of photos: Institut Géographique National, Paris)





**Fig. 3** Cross sections showing the present alluvial forest mosaic in relation to channel and floodplain topography, from 1998 field surveys. Cross section designations are based on distance upstream from the Rhône confluence,

i.e., CS 17.6 is 17.6 km upstream of the Rhône. Elevations are above arbitrary data at each site. Flow at time of field survey in June 1998 was approximately  $0.3 \text{ m}^3 \text{ s}^{-1}$ , a typical summer baseflow

parcels resulting from the division of land equally amongst all the children in a family. An example of the cadastral maps in the Commune of Vinsobres (Fig. 4) illustrates the complexity of land ownership and intensive land use. Summarizing over the entire study reach, the most common land use in parcels adjacent to the channel was *oseraie* (the term used in the Drôme, or from approximately km 25 upstream), or *hermes* (the term used downstream, in the Vaucluse) (Fig. 5). These units evidently contained willow stands

that were managed and frequently cut to yield materials for use in vineyards, in making baskets, wicker furniture, etc., and were also used as pasture of mediocre quality. That these units were productive and valued is evident on the cadastral map of the commune Saint Roman de Mallegarde, which was revised in 1828 to show newly subdivided land, in geometric parcels, reclaimed from the active channel of the Eygues and protected by a new dyke. This newly reclaimed land was designated as *nouvelles ramières*, or “new



**Fig. 4** Cadastral maps of the Eygues River (a) in the Commune of Vinsobres, 5 km downstream of Nyons at km 43, showing individual parcels, for each of which land use was recorded (1830); (b) land-use types by parcel superimposed on screened version of the Vinsobres map

(Source: Archives Départementales de la Drôme); (c) cadastral map of the commune of Saint Roman de Mallegarde (1828), showing area of newly reclaimed river bed used to grow willows, termed “new oeserie”



**Fig. 4b** continued

*oseraie*” (Fig. 4C). The next most common land use was plowed land or row crops, which often extended right down to the low-flow channel margins, which suggests pressure for arable land was enormous by the then-large rural population. Less common land uses adjacent to the low flow channel included (in order of importance) woodlots cut frequently, to leave only small trees, pasture, hayfields, vineyards, olive trees, roads, marsh, and domestic gardens (Fig. 5).

The extent of unvegetated active channel decreased as vegetation established, as illustrated in maps of active channel from Tulette to Cairanne (as visible on aerial photographs from

1947 to 1972 to 1996) (Fig. 6). The width of different vegetative units along the cross sections changed substantially (Fig. 7). In 1947, the cross sections were dominated by pioneer (early successional stage) vegetation (median width = 76.9 m), with pasture (maintained by grazing animals) important in some reaches (median width = 34.5 m). While the combined total area occupied by both pioneer and mature patches was roughly constant (345 ha in 1947 vs. 356 ha in 1996), many of the 1947 pioneer units had been replaced by mature forest in 1996. Open pasture vegetation was also lost to colonization by trees. In sum, the floodplain corridor changed from

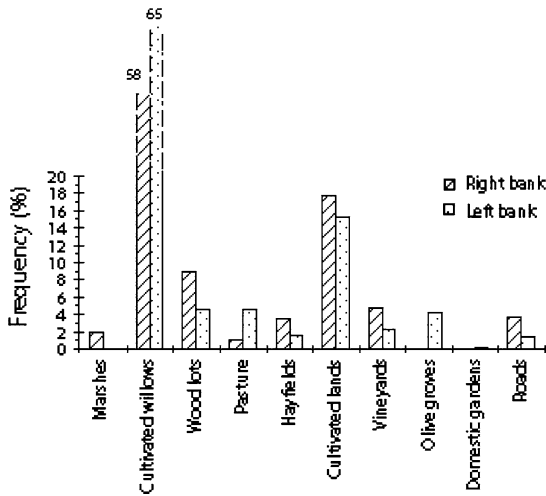




**Fig. 4c** continued

mostly pioneer vegetation intensively cut and grazed, large patches of pasture, and only small areas of mature forest, to mostly mature forest dominated by later successional species in 1996. Counteracting the expansion of forest into the former active channel and pioneer vegetation, the natural corridor was impacted by clearing for agriculture, recreation, mining and harvesting, which has fragmented the forest cover, as visible on the cross sections. For example, CS 44.2 has a corn plot, CS 39.1 a rubbish dump, and CS 33.2 and CS 24.5 both have deforested patches on the left bank. The median corridor width declined from 338 m in 1947 to 287 m in 1973 to 271 m in 1996 (Fig. 8). The area of riparian forest declined from 1132 ha in 1947 to 960 ha in 1973, mostly due to conversion to agriculture (89%) and secondly to gravel mining and storage sites. From 1973–1996, 108 ha of riparian forest were converted to other uses: agriculture (34 ha), gravel mining and storage areas (15 ha), harvested patches (45 ha), and urban and industrial areas (14 ha). The human pressure and corridor narrowing occurred mostly in the downstream reaches where the corridor was the largest in 1947, in the reach mainly located in the Vaucluse Department. Above Nyons, the riparian corridor had already narrowed by 1947.

These historical changes are illustrated for the cross-section at km 44.2 in Fig. 8, based on our field surveys in 1998, combined with analysis of aerial photographs of 1996, 1972, and 1947, and the cadastral maps (for this commune, dated 1826). The 1826 channel was approximately 500 m wide, extending from a terrace along the left bank across 330 m of unvegetated active channel and another approximately 170 m of *oseraie* to the right bank. A dyke originally constructed in the late 19th century along the right bank, thereafter constricted the channel width to about 350 m between the dyke and the terrace edge. The aerial photo of 1947 shows an unvegetated active channel of approximately 150 m width incised about 1 m below a floodplain, which was about 200 m wide and colonized discontinuously by pioneer vegetation. The floodplain itself was about 2 m lower than the 1830 channel, based on the elevation of the former channel surface behind the right bank dyke. The aerial photograph of 1972 shows a low-flow channel of approximately 20 m in width, further incised below the same floodplain as present in the 1947 photo. By 1972, the new floodplain was densely vegetated by a stand of poplar, with alder along the left margin below the terrace edge. By 1998, when we conducted our field surveys, there were two narrow channels



**Fig. 5** Percentage of different land use in parcels adjacent to the river channel as shown on Napoleanean cadastral maps 1824–1830

incised up to 4 m below the 1830 channel elevation, the extensive poplar forest visible on the left bank floodplain in 1972 had been largely eroded,

**Fig. 6** Extent of unvegetated active channel of the Eygues River from Cairanne (km 22.4) to Tulette (km 29) mapped from aerial photographs of 1947, 1972, and 1996

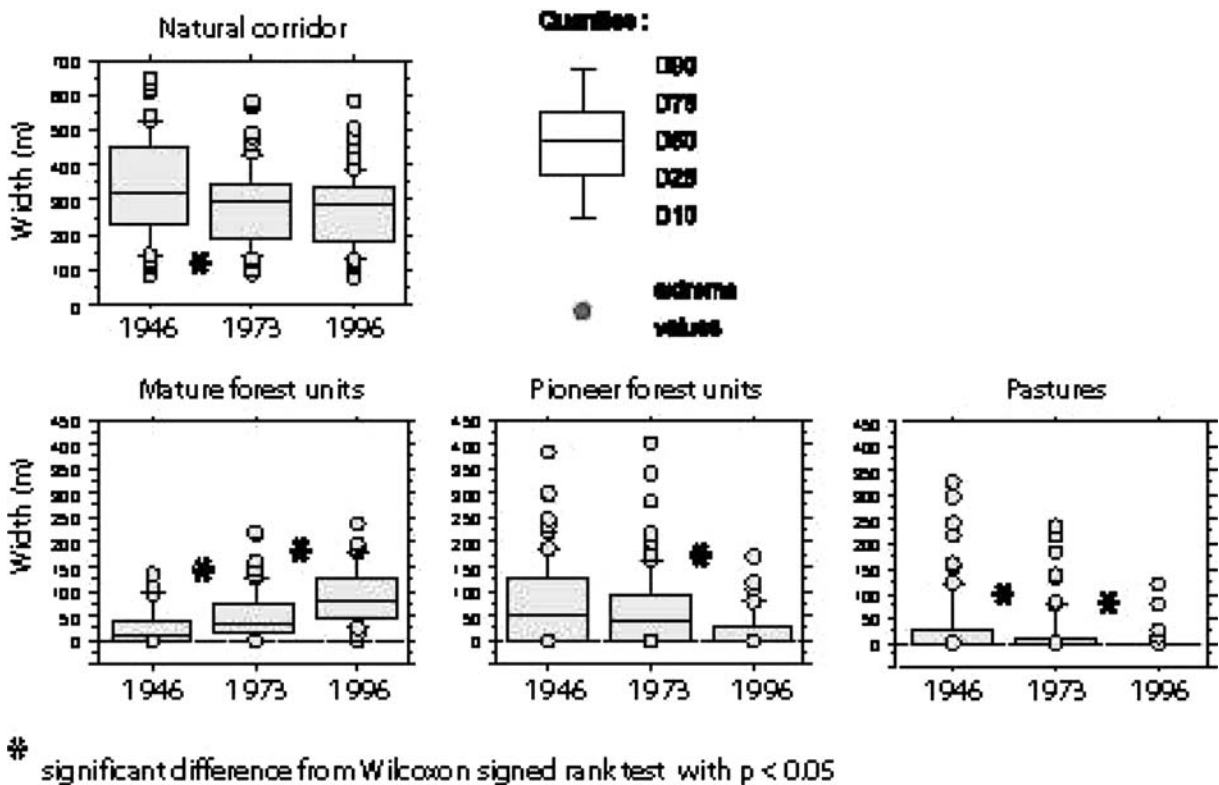
and the remaining 40 m of the former left-bank floodplain had been converted into corn field. The site of the 1998 corn field was an active channel 50 years before (Fig. 9).

Synchronous changes in channel geometry since the 19th century

Active channel width, as measured at 500-m intervals, narrowed from 1830 to 1947 in nearly all sections, and continued to narrow from 1947 to 1996 (Fig. 10). The median width of the active, unvegetated channel (from Nyons downstream) was 340 m in 1830, 200 m in 1947, 152 in 1972, and 139 m in 1996. When we add the 1947 transect widths occupied by pasture, pioneer and mature forest units to the active channel width, the combined natural corridor width is 338 m, roughly equivalent to the 1830 active channel width.

Comparison of long profiles surveyed in 1931 and 1985 clearly show incision (typically 1.5–3 m)





**Fig. 7** Distribution of the width of the different vegetative units in the valley corridor on aerial photographs of 1947, 1972, and 1996 ( $n = 67$ )

over this period from Nyons downstream to the Rhône, notably between Orange and the Rhône (−3.2 m) and downstream from Camaret-sur-Eygues (−5 m), but 1985–1997 surveys show a more complex picture, with some reaches stable, others slightly aggraded, mainly upstream of weirs or bridges (e.g. Travaillan bridge, Camaret bridge and weir) and downstream of the confluences of tributaries (e.g., Rieu de Vinsobres), whose sediment yield was high as they adjusted to the previous regressive erosion and as a result of the floods of 1992 and 1994. The 1997 bed averaged 1.3 m lower than the 1931 level, with degradation of 4 m near Nyons. The change in sediment storage by segment, calculated as the product of the incision or aggradation, segment length, and average segment width, was a loss of 9.8 million  $m^3$  1931–1985, and a gain of 1.3 million  $m^3$  1985–1997.

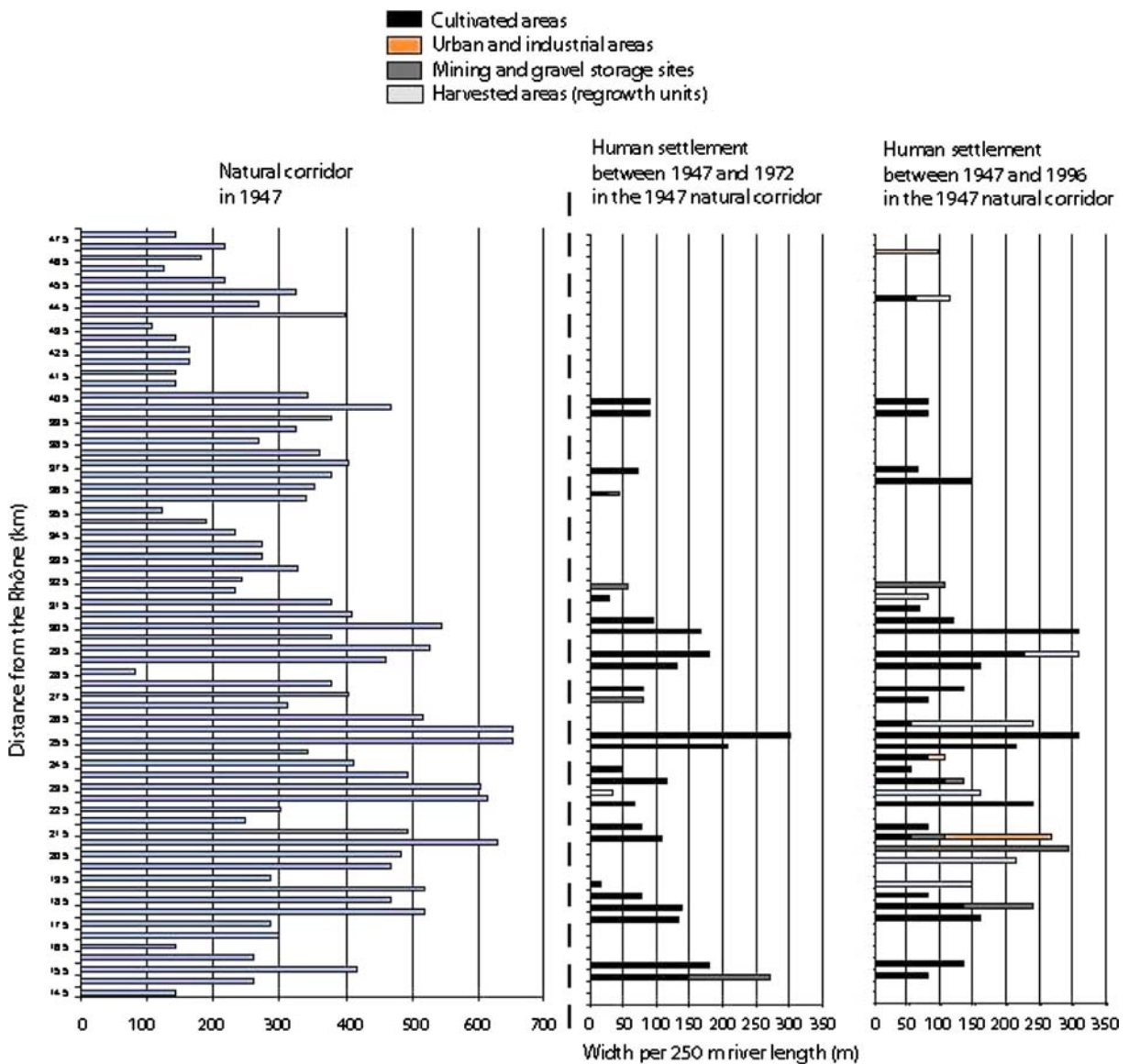
Cross section surveys (Fig. 3) showed that in three of the five cases, the current channel is 1–4 m below the level of the 1830 channel (now

preserved as terrace), but in CS 24.5 and CS 39.1, little or no incision was apparent. Along the right bank of CS 39.1, a former dump now functions as a dyke, constraining the channel. There is a wide variation when comparing the current channel width with past channel widths (shown in Fig. 3 by arrows) measured from aerial photographs.

## Discussion

### Synthesis of changes

In 1830, the entire catchment was populated and human pressure was high. The mountains were devegetated, thus with high sediments yields, resulting in a wide, aggraded channel. Floodplain agriculture extended literally to the channel edge. Since then, reduced sediment supply led to channel narrowing and incision, agricultural pressure has decreased, and former active channel areas have been colonized by riparian forest,



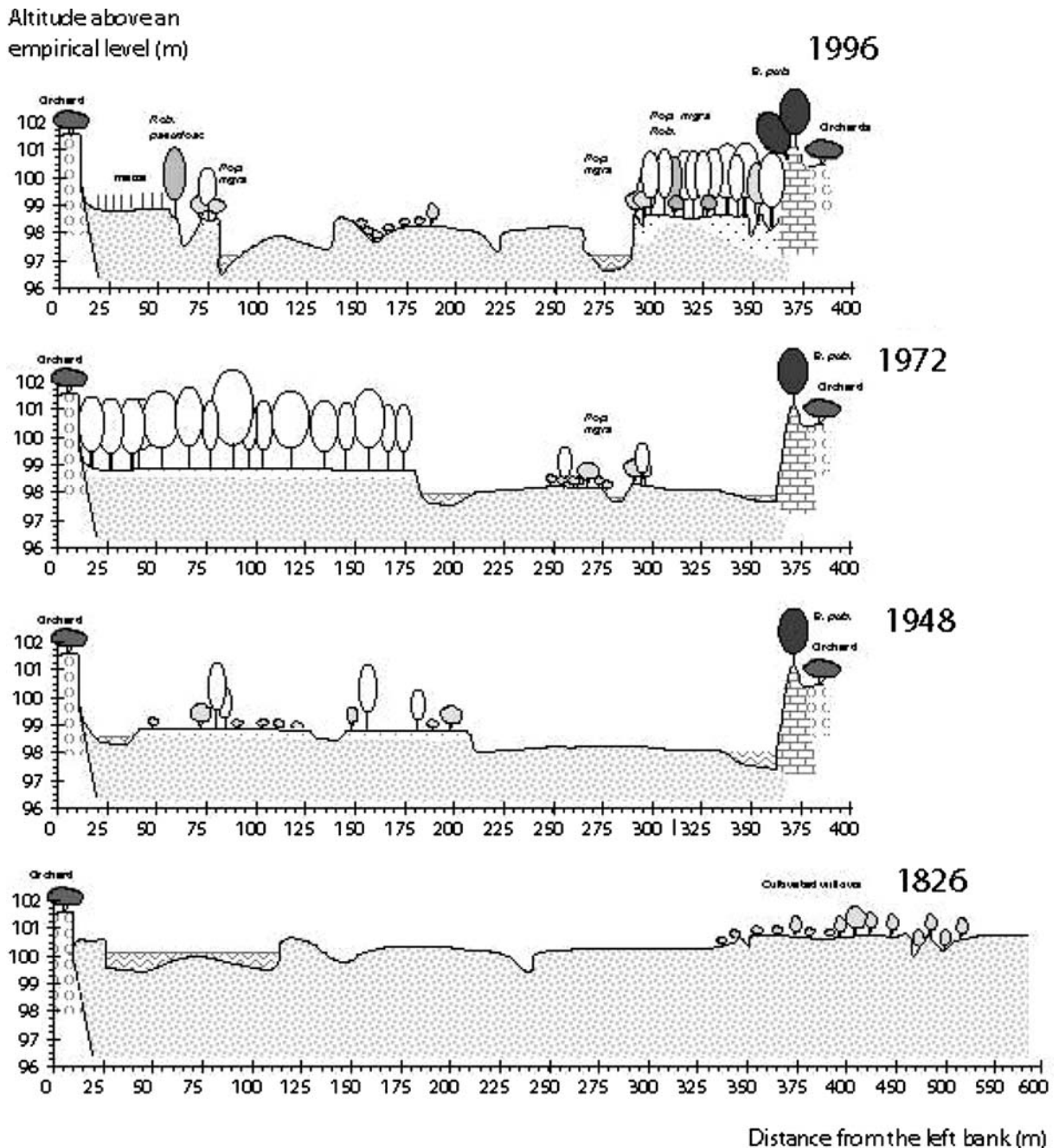
**Fig. 8** Longitudinal distribution of the natural corridor width in 1947 and of the human settlements in the 1947 corridor between 1947 and 1972 and between 1947 and 1996 per 250 m length segments between km 14.5 and km 47.75

much within late 19th and early 20th century flood dykes. In recent decades, aggregate mining, development of recreation areas, and agricultural fields have fragmented this riparian forest. As forest cover in the catchment continues to increase, flood magnitudes in the river are likely to decrease (ignoring potential effects of climate change), reducing flood risk to agricultural uses and hence increasing the likelihood of further clearing for agriculture.

#### Causes of channel changes and consequences for the riparian corridor architecture

Reduction in coarse sediment yield from the catchment was progressive over decades in the 20th century, reflecting the time needed for formerly active sediment-producing tributary channels to become “extinct” (evident on air photos from 1947 to 1972 or 1996, where formerly wide, open tributary channels evolved to narrow channels flanked



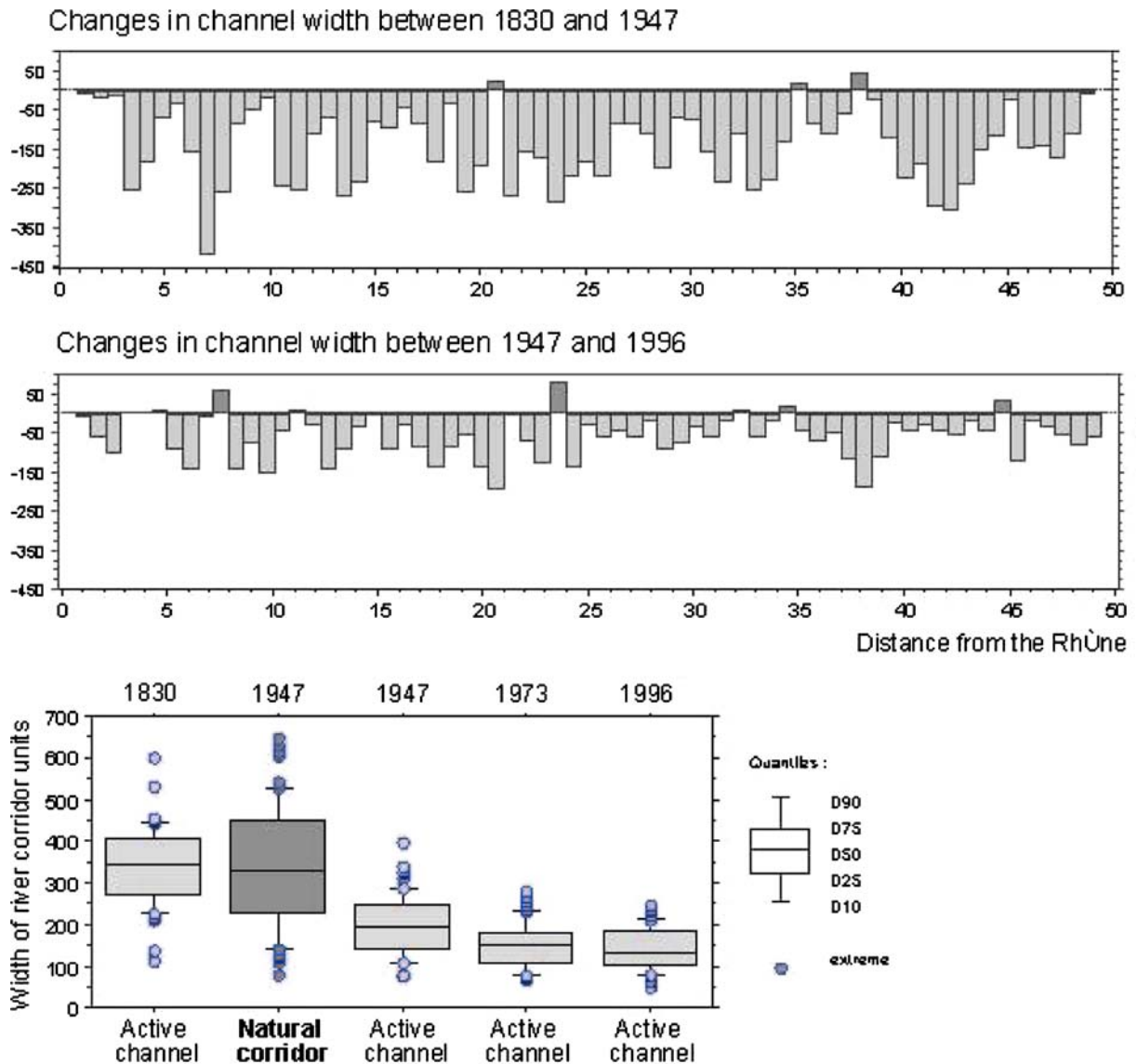


**Fig. 9** Cross sections at km 44.2 showing riparian landscape changes from 1830 to 1998. Vegetation and topography for 1998 were field surveyed (at a discharge of about  $0.3 \text{ m}^3 \text{ s}^{-1}$ , typical summer baseflow). Vegetation communities for 1830 were reconstructed from cadastral maps, for

1947 from aerial photographs. Topography for 1830 and 1948 was reconstructed from comparing historical maps and photographs to current topography, and from long profiles surveyed in 1931, 1985, and 1997

by dense riparian forest), and the lag time required for effects of sediment starvation to propagate downstream (Liébault et al. 2002).

Increased forest cover in the catchment induced a reduction both in sediment supply and in peak flows, explaining a synchronous channel

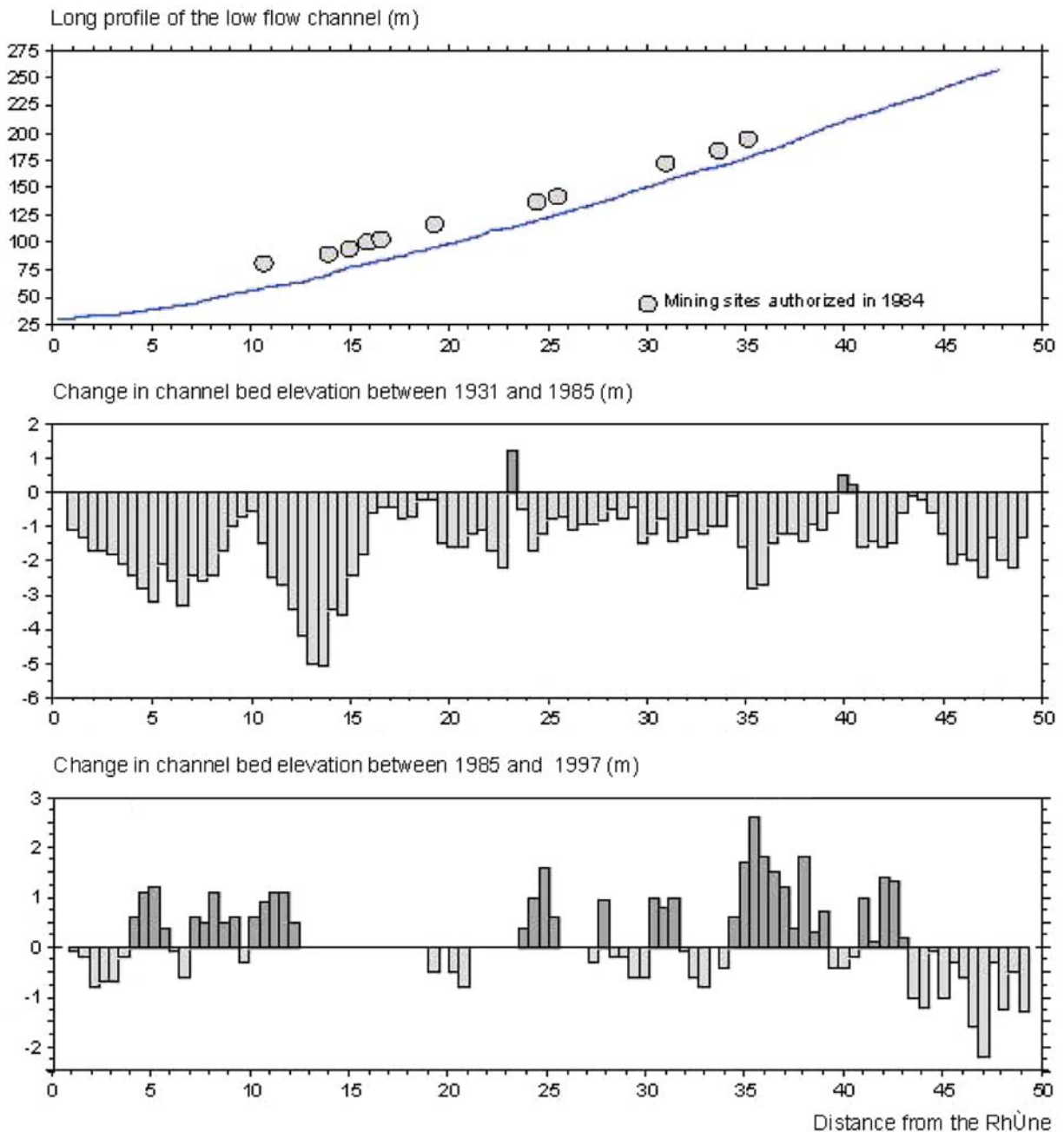


**Fig. 10** Evolution of channel width in the Eygues River downstream of Nyons. (a) Changes in channel width from 1830 to 1996, (b) Changes in channel width from 1947 to 1996, (c) Distribution of channel width per 500 m length

segments in 1830, 1947, 1972 and 1996 and of natural corridor (channel and uncultivated riparian zone) in 1947, based on analysis of aerial photographs

narrowing at the catchment hydrographic network scale, and in neighboring catchments of the Roubion and Drôme (Liébault and Piégay 2002). In the mountainous part of the basin, upstream of Nyons, the Eygues and its major tributaries have incised 1.5–3.0 m below former channel surfaces, and sequential aerial photographs showed that average channel widths in 1996 were only 40% of

their 1947 values, though actual narrowing varied widely among channels throughout the upper basin (Liébault et al. 2002). One consequence of the channel narrowing has been the establishment of a riparian forest on abandoned areas of the formerly active channel, in some cases in between dykes constructed in the early 20th century, when the active channel was much wider. Even in the



**Fig. 11** Channel incision from 1931 to 1985, and 1985 to 1997, measured from surveys conducted in 1931 by *Service des Grandes Forces Hydrauliques* (a state service charged

with locating sites suitable for hydro-electricity production), in 1985 by SOGREAH (1987), and in 1997 by CNRS (Landon and Piégay 1999)

absence of incision, the channel probably would have narrowed, because with the reduced bedload sediment supply and transport, the Eygues could no longer maintain its wide 19th century channel. Incision would accelerate narrowing, as the inci-

sion would be concentrated in a narrow channel, leaving the rest of the formerly active channel isolated above the low-flow channel elevation, thus less likely to be eroded in floods, and therefore suitable for colonization by riparian vegetation.

**Table 1** Total area (hectares) occupied by different landscape units in 1947, 1973 and 1996 (mapped from air photos). The area mapped was the natural corridor identified on the 1947 photos

	1947	1973	1996
Natural corridor	1132	961	908
Active channel	670	510	478
Mature forest units	89	170	299
Pioneer forest units	257	218	69
Pastures	116	74	16
Agricultural units	0	130	164
Gravel storage	0	15	29
Urbanised areas	0	0	14
Spontaneous regrowth units*	0	0	45

\*after clear-cut or agricultural and mining abandonment

At the end of the 19<sup>th</sup> century, the (newly-created) Service de la Restauration des Terrains de Montagne (RTM) began planting of black pine trees (*Pinus nigra*) on mountain slopes and installing check dams in torrents to reduce erosion. The erosion control efforts may have contributed to the decline in sediment yield from pre-Alpine river catchments after the late 19th century, causing river channels to incise over the region. However, in the catchment of the Eygues, this effect was minor compared to the Drôme River catchment: only 1240 ha were deliberately afforested in the Eygues vs. 15000 ha in the Drôme, and only 1400 checkdams installed in the Eygues vs. 9100 in the Drôme. Even in the Drôme, the role of RTM works was minor compared to the spontaneous increase in forest cover (Liébault and Piégay 2002), so we would expect that the influence of the RTM works on the Eygues to be negligible considering the smaller effort there.

In the channel downstream of Nyons, a major cause of 20<sup>th</sup> century incision was sand and gravel mining. This reach of the Eygues was an important source of construction aggregate, with about 8 million m<sup>3</sup> removed from 1970–1990 from multiple locations (Fig. 11) (SOGREAH 1987), roughly comparable to the 9.8 million m<sup>3</sup> reduction in channel storage since 1931 estimated from morphological changes. Since prohibition of most instream aggregate mining in 1992, the bed has partially recovered through aggradation.

## Riparian forest establishment

The recent development of a diverse riparian forest reflects the self-restorative potential of a dynamic river such as this, and specifically the lateral connectivity between the channel and floodplain, and adequate coarse sediment supply. As the channel recovered from the high sediment loads and intense agricultural use of riparian lands, the riparian forest spontaneously established on previous pastures unit as well as active channel area. However, the active nature of the channel means that the riparian forest is frequently disturbed, and succession interrupted, such that the riparian forest is dominated by pioneer and mid-successional stage stands. This pattern is in contrast to spontaneous riparian forests developed downstream of dams in the 20th century, which due to decreased flood frequency and magnitude are inactive and may be dominated by later-successional stage species (e.g., Johnson 1992). The riparian regeneration manifest along the Eygues might not be possible along deeply incised channels, because the alluvial water tables might be too low to support development of new riparian forest.

We speculate that in some reaches, construction of dykes in the 19th or early 20th centuries—instead of late 20th century—may have contributed to keeping the riparian forest undisturbed in recent decades. Our observations suggest that when dykes are constructed, they are typically built just outside the current active channel. For example, at CS 44.2, a dyke was built along the right bank in the late 19th century, probably at the margin of then-wide active channel, or even within it, to reclaim land from the river (Fig.3). Because the active channel subsequently narrowed, it left room (between the dyke and the older terrace edge defining the left bank of the fluvial corridor) for riparian forest to develop and within which the active channel could freely migrate. If instead the river had been dyked after the Second World War, the dykes would probably have defined a narrower corridor, roughly equivalent to the width of the then-active channel. At CS 44.2, this might have involved constructing a dyke along the left bank to protect the floodplain for agriculture.



## Implications for setting restoration goals

Restoration of river channels and riparian forests is often undertaken based on characteristics of a reference site, believed to reflect natural, undisturbed conditions. In North America, pre-European conditions are often thought of as pristine, though in fact native Americans were present and affecting the landscape long before Europeans colonized the continent. In Europe, human occupation has been so pervasive for so long that it is essentially impossible in most places to define a pristine, pre-human-disturbance condition. Even if such a condition could be divined, it is not necessarily what the societies would choose for a restoration goal, as many of the prized landscapes are those maintained by traditional agriculture, such as the pastures maintained by grazing livestock. The historical perspective is important so that we know where we've been and how we got where we are today, but it cannot be expected to provide restoration goals per se, as these must take into account current human uses, societal landscape preferences, and biodiversity (Kondolf and Larson 1995).

Along the Eygues River, the historical evidence shows that the riparian forest existing today, identified by the EU as of ecological importance, was not present in the mid-19th century because of intense human pressure (1) along the river banks and floodplain, where virtually every square meter was used to grow something useful, and (2) in the mountains, where intensive grazing and wood-cutting gave rise to high sediment yields, which in turn aggraded the downstream channels. Thus, the 19th century condition represented an already-degraded condition, and would probably not be appropriate as a reference condition for restoration.

The riparian corridor is larger today than it was 50 years ago, but channel behavior is less dynamic (with lower sediment supply), and channel incision has dried out some river margins. Moreover, new human pressures have resulted in patchy deforestation, and construction of buildings on the floodplain will likely create a demand for levees or other flood control in the future. Thus, we can view the evolution of the riparian corridor on a historical trajectory. From current trends, we

can predict increasing human pressure on the corridor, notably deforestation just as the forest becomes older, continued channel narrowing as bedload supply continues to decrease, reduced lateral migration, and a less diverse riparian forest, increasingly dominated by later successional species.

The riparian landscape that we value and seek to preserve today is a cultural landscape, with structure and function reflecting human influences. The pasture vegetation along the Eygues, which includes some rare species, was historically maintained by livestock grazing, and is now the subject of ongoing preservation efforts against spontaneous encroachment of forest (Michelot 1995). In this context, the concept of a “reference” state is ambiguous at best. Preservation efforts can be undertaken to save the last natural patches of ecological interest, as recognized by the Natura 2000 program (<http://www.natura2000.environnement.gouv.fr/sites/FR8201689.html>). However, these landscape units are becoming progressively less riparian and more xeric in character due to less frequent flooding, and they face increasing human pressure for timber harvest or conversion to vineyards. For the Eygues River, we propose that appropriate restoration goals might be a river condition that supports human uses and ecological functions over a long period of time. Human uses such as agriculture on the floodplain could be compromised by excessive aggradation of the channel, which might increase the risk of flooding and avulsion. A “buffer” of natural forest between the active channel and cultivated land benefits the agricultural lands subject to inundation by filtering large wood, coarse sediment, and other debris from the floodwaters. Habitat values are greater in an alluvial forest that is longitudinally continuous (not degraded by dumping, filling, or aggregate extraction) and with high species diversity maintained by periodic channel migration, erosion of older forest units, and invasion of pioneer units on recently deposited bars. If dykes are constructed, they should be well outside the fluvial corridor (which we define as the active channel and riparian corridor combined), not just outside the current active channel. We would not propose to ask farmers to abandon land that has

been under cultivation for centuries, but we would propose that agriculture be abandoned within the fluvial corridor, so that the alluvial forest that spontaneously developed within the 1830 channel bed in the 20th century be preserved and restored. The aim is to optimize the present human uses and to preserve the natural corridor architecture not only for its inherent ecological value but to satisfy future human needs on a sustainable basis.

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